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A physically based trunk soft tissue modeling for scoliosis surgery planning systems

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ABSTRACT

One of the major concerns of scoliotic patients undergoing spinal correction surgery is the trunk's external appearance after the surgery. This paper presents a novel incremental approach for simulating postoperative trunk shape in scoliosis surgery. Preoperative and postoperative trunk shapes data were obtained using three-dimensional medical imaging techniques for seven patients with adolescent idiopathic scoliosis. Results of qualitative and quantitative evaluations, based on the comparison of the simulated and actual postoperative trunk surfaces, showed an adequate accuracy of the method. Our approach provides a candidate simulation tool to be used in a clinical environment for the surgery planning process.

1. Introduction

Adolescent idiopathic scoliosis (AIS) is a complex three-dimensional deformation of the trunk. In severe cases, a spine surgery treatment is required. Most of the surgical procedures use specialized instrumentation attached to the spine to correct the deformities. Fig. 1 shows the radiographs of the same scoliotic patient subject before and after a spine surgery. The postoperative radiograph (on the right) clearly exhibits the metallic instrumentation used to correct the spine curvature. One of the concerns of the patient (and, in fact, a major factor of satisfaction) is the trunk's appearance after the surgery. In addition to the surgeon's priorities in the surgery planning process, a tool for simulating the trunk's postoperative appearance is of importance to take into account the patient's concerns in the treatment planning.

Aubin et al. [1] have developed a spinal surgery simulation system in the context of the optimal planning of surgical procedures to correct scoliotic deformities. The overall goal of this biomechanical engineering research project is to develop a user-oriented simulator for virtual prototyping of spinal deformities surgeries: a fully operational, safe and reliable patient-specific tool that will permit advanced planning of surgery with predictable outcomes, and rationalized design of surgical instrumentation [1,2]. It addresses the problems faced by orthopedic surgeons treating spinal deformities when making surgical planning decisions. The developed system is, however, only concerned with the configuration of the spine, and does not furnish any estimate of the effects of the surgical treatment on the external appearance of the trunk. A desirable complement to this spine simulator would be to develop a full trunk model that would allow the propagation of the surgical correction on the spine toward the external trunk surface through the soft tissue deformation.

Physics-based models of deformable objects have been studied since the early 80's and are common in animation where physical laws are applied to an object to simulate realistic movements. Deformable physics-based models are also used in biomedical applications, in particular for surgery simulation [3]. These applications require visual and physical realism, but the real biomechanical properties involved are not always well known. The two most popular approaches to physically modeling soft tissues are the Finite Element Method (FEM) and Mass-Spring Model (MSM). Commonly used in engineering to accurately analyze structures and continua, the conventional FEM still has a large memory cost and computation times that limit interactive applications. For example, computations times reported in [4] are in the range of 8 min for a model of size of 7 k nodes on a personal computer equipped

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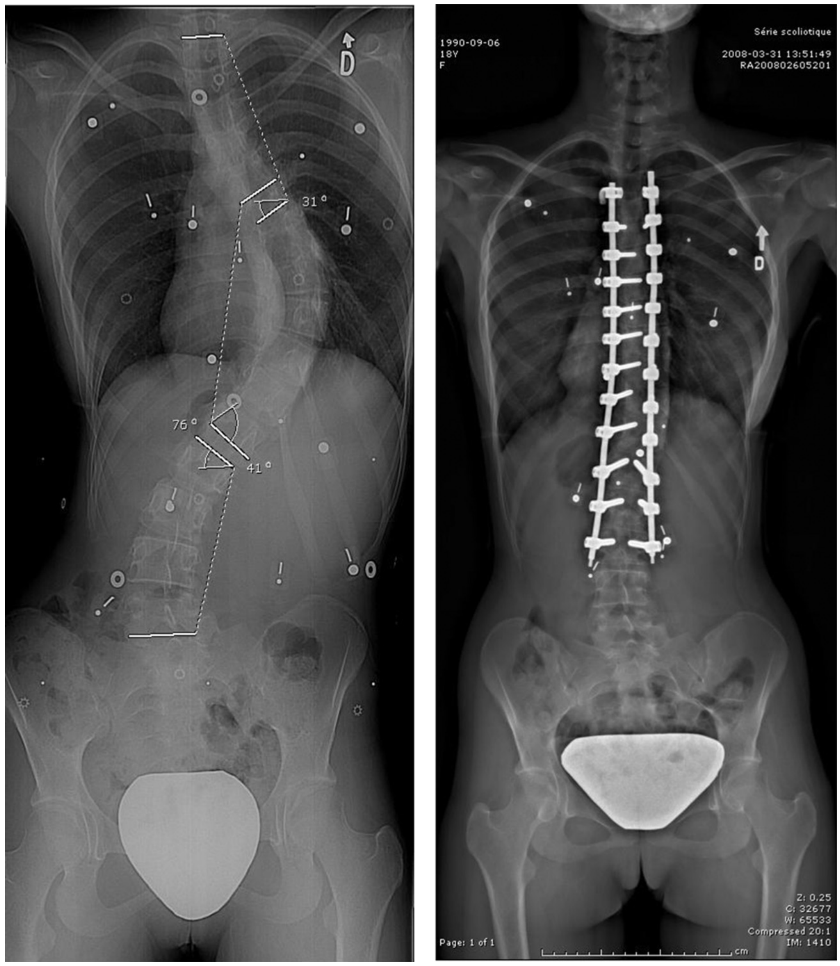

Fig. 1. Surgical instrumentation of a scoliotic spine for the correction of spinal deformities. Left: preoperative radiograph. Right: postoperative radiograph. The radiographs were obtained from the same scoliotic patient subject before and then after the spine surgery. The metallic instrumentation attached to the spine is clearly visible on the postoperative radiograph.

with CPUs hardware architecture. Variants of FEM-based methods have thus been introduced to solve these issues [5–7]. However most of them are applicable only to linear deformations valid for small displacements. Improvements have been made to include large deformations in real-time [8] but a small number of elements must be considered in order to attain interactivity due to the increased computational cost. Application examples are the simulation of plastic and maxillofacial surgeries [9–11] and breast reconstructive surgery [12]. The MSM approach is less physically accurate than continuum biomechanical models. Nonetheless, with different stiffness springs, Terzopoulos and Waters [13] animated a face composed of several layers of springs representing the epidermis, dermis, sub-cutaneous connective tissue, fascia and muscles. A generic model was adapted to real digitized faces by an optimization of the masses' positions using facial features [14]. Koch et al. [9] used a finite element surface connected to the skull by springs to simulate a facial plastic surgery. The MSM approach has also been used to model hip joint replacement [15]. In general, mass-spring methods have many advantages: simple implementation, intuitiveness, efficiency, good first interactive impression and easy parallelization. On the other hand, classical MSM present some disadvantages: (i) since no volume behavior of the tetrahedra is incorporated into the model, flip-over of springs may possibly occur and (ii) there is no way to control the volume conservation during simulation.

In general, large deformations of soft tissue are dealt with by introducing nonlinearities in the formulation of the tissue properties. Nonlinear elasticity has been proven to yield better results as compared to linear elasticity in the case of large deformations [7,8]. However, the complexity of the computation is increased with this solution. In this paper, we propose a novel incremental approach for simulating the trunk shape correction that takes into account the large deformations involved in the preoperative-to-postoperative changes, while maintaining the linear approximation. The main idea consists in reducing the nonlinear deformation process into a sequence of small deformations for which the linear elastic behavior holds, so that one can keep the initial linear formalism in the course of the simulation. The method is then applied to a set of real data of scoliotic patients ($n = 7$) who have undergone spine surgery and for whom preoperative and postoperative data are available.

2. Methodology

2.1. The scoliotic patients sample

Consenting AIS patients ($n = 7$) with thoracic (spinal) curve having undergone corrective spine surgery at Sainte-Justine University Hospital Center (SJUH) in Montréal, Canada were considered. The hospital's Research Ethics Committee has approved the study protocol. The average patient age at the time of surgery was 13.9 ± 1.5